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Woods Hole Oceanographic Institution

Altimeter Analysis Of Ocean Currents

by

Sandipa Singh, Michael J. Caruso and Kathryn A. Kelly

July 1994

Technical Report

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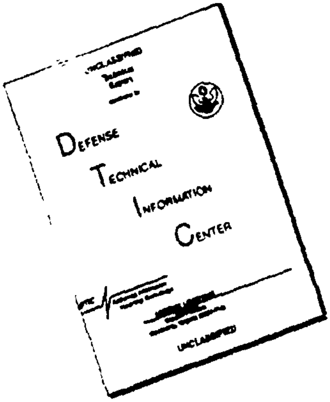

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Abstract

Altimeter data from satellites are being used in an ongoing effort to obtain data sets with temporal as well as global coverage. This report describes the algorithms formulated and the programs written for the use of altimeter data from the European Space Agency (ESA) European Remote Sensing Satellite, ERS-1, for a repeat track analysis of ocean currents. It also presents some results from the California Current region.

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1 Introduction

This report describes the use of altimeter data from the European Space Agency (ESA) European Remote Sensing Satellite, ERS-1, for the analysis of ocean currents. It is the continuation of the altimeter analysis developed previously by Caruso *et al.* [1990] for the U.S. Navy altimetric satellite, GEOSAT. The common purpose of both projects was to perform a 'repeat' or 'collinear' track analysis, which required sorting the data into collinear tracks, correcting the sea-surface heights for various measurement errors, and regridding the along-track data to a common grid [1].

The major difference between the two projects is that the ERS-1 satellite has two phases. The first phase consists of a three-day repeat orbit and the second phase consists of a 35-day repeat orbit. The satellite remains in the first phase for the first three months of the year, and then switches to the second phase for the rest of the year. This has necessitated the rewriting of several of the GEOSAT data-processing routines so that they can work on the two unique ERS-1 orbits. Since the processing is similar for the GEOSAT and ERS-1 altimeters, an effort was made to use as many of the GEOSAT analysis programs as possible. This report presents the similarities and differences in the two data sets and the modifications that were made to accommodate the ERS-1 data.

Section 2 describes the format in which the raw data are stored and the routines needed to convert it to the GEOSAT format. Section 3 describes the orbit parameters and characteristics for the two phases of the satellite. Section 4 outlines the steps required to label and store the data according to phase, cycle and orbit numbers so as to facilitate repeat track analysis. It then analyzes the relabeled data from the California Current region for the derivation of mean sea surface heights. Section 5 shows some results obtained from the analysis performed in section 4. Finally, section 6 contains descriptions of the various C-program routines.

2 Geophysical Data Record, IGDR

The raw altimeter data are processed by the National Oceanographic and Atmospheric Administration (NOAA), using programs which merge ephemerides information and add corrections for tides and travel times. Each geophysical data record, called an IGDR, is 64 bytes long. Henceforth, GDR will refer to a GEOSAT geophysical data record, whereas IGDR will refer to an ERS-1 geophysical data record. In order to take advantage of the routines already written to process GEOSAT data, the IGDRs were rewritten in GDR format using the routine *ers2geos*. Table 1 shows the mapping of the ERS-1 IGDR fields (in column two) into the GDR fields (column three). The parameters connected with wind speed statistics (fields 11, 12 and 13), corrections to the height relative to the reference ellipsoid (field 20), integrated electron density (field 22), and peakiness (field 23) did not have corresponding GDR fields. However, they were not needed for this analysis and were, therefore, discarded. The flag, which was included as a part of an IGDR, was stored separately to conform with the GDR format. Table 2 shows the mapping of the flag bits. Information from only two flag bits was retained, bit 0, which indicates a measurement over water, and bit 1, which indicates a shallow water measurement. Column three in both tables can be used as a cross-reference to Table [illegible] in the report by Carnes *et al.* (1990).

3 Orbital Characteristics

The ERS-1 satellite has two separate orbits for its two phases. Global coverage for phase one is depicted in Figure 1. Figure 2 shows coverage for phase two within the Northwest Pacific region since individual tracks would be indistinguishable in a global coverage plot for this phase. Phase one is marked by a three-day repeat period and thus provides good temporal coverage. However, the spacing between tracks is approximately 2° of longitude. Phase two is marked by a 35-day repeat period with the spacing between tracks reduced to approximately [illegible]° of longitude.

The IGDRs do not explicitly store phase information and so, in order to calculate start and end times for each phase every year, the time period for each cycle is calculated. When this period shifts from three days to 35 days, it marks the transition from phase one to phase two. Orbital period can be calculated by dividing the cycle period by the number of orbits in each cycle. Table 3 summa-

Table 1: Geophysical Data Record Contents

Item	ERS-1 IGDR Parameters	GEOSAT GDR Parameters	Units	Range	Bytes
1	UTC(Since 1/1/85)	utc	s	2^8 to 5^8	4
2	UTC(contd.)	utcm	s $\times 10^{-6}$	0 to 1^6	4
3	Latitude	lat	Degrees $\times 10^{-6}$	$\pm$ 8.2^7	4
4	Longitude	lon	Degrees $\times 10^{-6}$	0 to 3.60^8	4
5	Orbit	orb	mm	7.7^8 to 8.1^8	4
6	Flags	(see text)			4
7	H (uncorrected)	m_h	cm	$\pm$ 1.5^5	4
8	Sigma (H)	s_h	cm	0 to 100	2
9	SWH	swh	cm	0 to 2500	2
10	Sigma (SWH)	s_swh	cm	5 to 100	2
11	Wind Speed	(not used)	0.1 m s^{-1}	0 to 350	2
12	Sigma (Wind Speed)	(not used)	0.1 m s^{-1}	0 to 35	2
13	No. in Average	(not used)		10 to 20	2
14	Geoid	geoid	cm	$\pm$ 1.5^5	2
15	Solid Tide	s_tide	mm	$\pm$ 500	2
16	Ocean Tide	o_tide	mm	$\pm$ 5000	2
17	Wet (NMC)	w_fnoc	mm	0 to −400	2
18	Dry (NMC)	d_fnoc	mm	−2100 to −2400	2
19	Iono	iono	mm	0 to −200	2
20	H Corrn. (Cal)	(not used)	mm	$\pm$ 1000	2
21	Sigma-Naught	s_naught	0.01 dB	0 to 4000	2
22	Int. Electron Dens.	(not used)		1^4 to 2^4	2
23	Peakiness	(not used)	0.01	100 to 170	2
24	Wet (SMMR)	w_smmr	mm	0 to −400	2
25	Wet (SMMI)	w_smmi	mm	0 to −400	2

Table 2 Flag Contents

Bit	IGDR Parameter	GDR Parameter
0:	Set to 1 if over water, based on 1/12th degree land mask	w
	Set to 0 if over land	
1:	Set to 1 if over water > 225m, based on 1 degree mask	d
	Set to 0 if over shallow sea < 225m, or over land	
2:	Set to 1 if daily solar flux value out of [illegible] mode range	
3:	Set to 1 if time gap > 12 hours in NMC wet [illegible] interpolation	
4-7:	Reserved for future NOAA flags	
8-15:	URA Product Confidence	
16-23:	Calibration Status	
24-31:	Instrument mode	

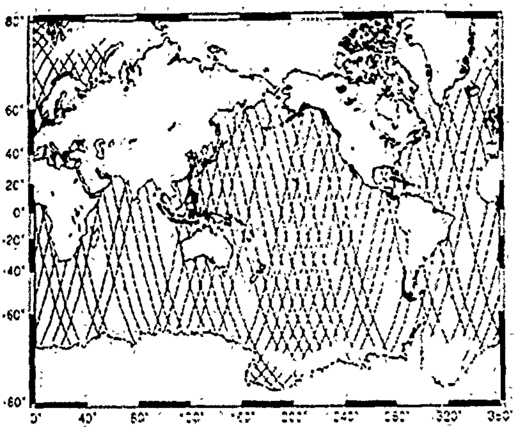

Figure 1: Orbit tracks for one complete cycle in phase I

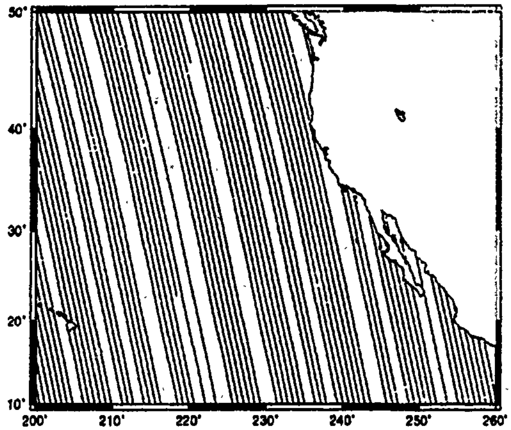

Figure 2: Ascending orbit tracks for one complete cycle in phase 2 (1993 data): Northwest Pacific region

Table 3: Orbital Parameters

Parameter	GEOSAT	ERS-1, Phase 1	ERS-1, Phase 2
Cycle Period (days)	17	3	35
Orbital Period (seconds)	6037.55	6027.91	6035.94
Orbit Inclination (degrees)	107.98	98.516	98.543
Ascending Node (degrees longitude)	356.5876	24.36	20.96
Orbits Per Cycle	244	43	501
Reference Date	January 1, 1985	January 1, 1985	January 1, 1985
Start Time for 1992 (seconds)	58403168.68	221171732.92	229207416.26
Start Time for 1993 (seconds)		252620775.26	265495424.13
Spacing between successive data points (seconds)	0.98	0.98	0.98
Intra-cycle track spacing (degrees longitude)		2	0.2
Number of cycles	50	30	8

rizes these, and some other statistics on the two phases and compares them with the GEOSAT data orbit. It can be seen that the two satellites have very different orbital characteristics and thus data from both cannot be merged for collinear analysis.

4 Repeat Track Analysis

Although an effort was made to use the programs written for GEOSAT processing by converting the data from IGDR format to the old GEOSAT format, several programs required specific orbit information and needed to be modified. These programs are relabeled with an *i* preceding their old name. The essential difference between the old and the new routines is the calculation of orbital parameters, such as period and inclination, based on the determination of phase by looking at the time record.

4.1 Orbit Numbering

In order to carry out repeat track analysis of the Northwest Pacific Ocean region, data from that region are first extracted with each record being labeled with a phase, cycle and orbit number (see Table 4). Orbits are numbered sequentially and are distinct for each phase. Phase one has 43 orbits and phase two has 501 orbits. A new cycle is started when the satellite begins to repeat during each phase, 3 days for phase one and 35 days for phase two. Thus, a GDR from phase one, cycle one and ascending orbit one of the satellite would be labeled: *p1c001a001*. This can be done using the program *[illegible]*. Data from the two years, 1992 and 1993, can be analyzed together. However, data from the two phases cannot, since the satellite orbits are different for the two phases.

Once data from a particular region are extracted and labeled, phases one and two can be put in separate directories, since information from them cannot be analyzed together at this stage. Within each phase directory, each cycle is given its own separate subdirectory. Thus, to continue the previous example, the GDR *p1c001a001* from year 1992 would be stored in the directory 1992/p1/c001.

Table 4: Naming Conventions for record *plcmmm.onnn*

number	description	range
l	phase	1 (3-day)
		2 (35-day)
mmm	cycle	000–029 (for l=1)
		000–007 (for l=2)
o	orbit	a (ascending)
		d (descending)
nnn	orbit	000–042 (for l=1)
		000–500 (for l=2)

4.2 GDR Processing

After the GDRs have been split into individual orbits for the region of interest, they must be filtered, corrected and regridded. The original GEOSAT filtering routines, *g_clean2* and *g_spike* and correction routine, *g_correct*, were used without modification. The splining of the cleaned data to a uniform rectangular grid is carried out using the routine *ig_spline* (Section 6.4), which is a modified version of the GEOSAT *g_spline* routine.

Once all the GDRs are cleaned, corrected and regridded, they can be analyzed using the modified repeat analysis routine, *ig_repeats* (Section 6.3). This routine calculates mean sea surface height from repeat-track data and subtracts it from each cycle. Orbital errors are removed by fitting a sine function (one cycle per revolution), to the residuals and subtracting it.

4.3 Calculation of Geostrophic Velocities

The final stage is to calculate geostrophic velocities, using *ssh* (sea surface height) residuals. The relationship between *ssh* and geostrophic velocity, V [2], is:

$$V = \left(\frac{-g}{f_c}\right)\left(\frac{\delta h}{\delta x}\right) \qquad (1)$$

where:
g is gravitational force = $9.8ms^{-2}$,
f_c is the Coriolis force = $2\Omega sin\theta_{lat.}$,
δh is *ssh* difference between two successive points on the track (meters), and

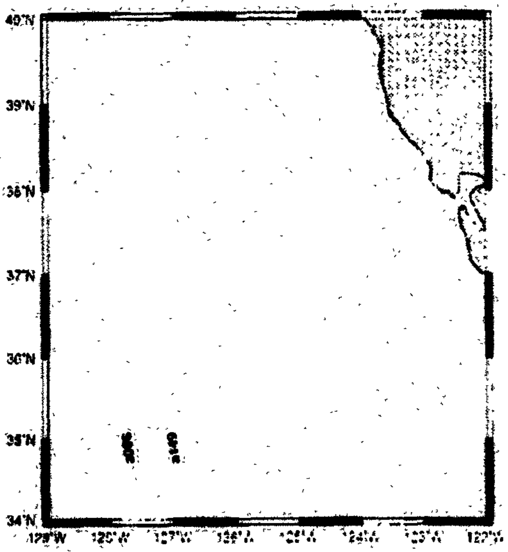

Figure 3: ERS-1 ascending subtracks along the California coast

δx is distance between two successive points on the track (from south to north, in meters).

The next section describes the implementation of the above method to ERS-1 data from the California Current region and discusses the results.

5 Results

The California Current region was analyzed using ERS-1 data from the years 1992 and 1993. The results presented in this section deal exclusively with subtrack a006 from phase one and a149 from phase two. Figure 3 shows the satellite subtracks used in the analysis. Subtrack a149 is approximately [illegible] km away from the coast at 39° of latitude while subtrack a006 is [illegible] km away.

Figure 4 shows data from subtrack a149. There are five profiles from 1992 and two from 1993. The plot of the unfiltered height residuals shows 1992 data to be noisier than the 1993 data. In particular, the May 1992 profile shows height

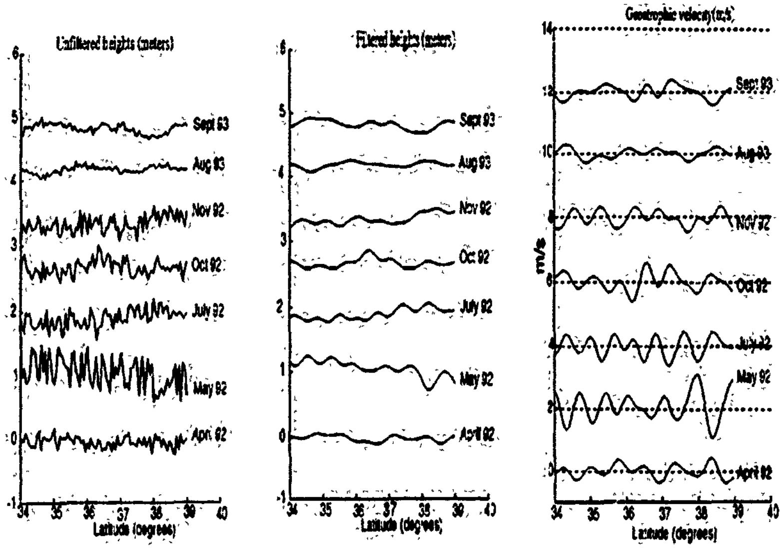

Figure 4: Unfiltered *ssh* residuals, filtered *ssh* residuals, and geostrophic velocity for 7 profiles along subtrack a149

jumps of over 50 cm. In order to smooth out the noise the profiles were low-pass filtered. Though the plot of the filtered heights shows better results, there is nothing consistent between profiles that could be taken as an indication of a jet. Also, the 50 cm jump has not been entirely removed. The final plot of geostrophic velocity was obtained from *ssh* residuals using equation [illegible]. Since the velocity is really a differential of the height, we should expect to see negative (offshore) velocities where the *ssh* has a positive slope, and positive (onshore) velocities in areas where the *ssh* has a negative slope.

A similar analysis was performed on subtracks a006 to obtain geostrophic velocity profiles for phase one. Values for the root-mean squares of the offshore and onshore velocities were calculated separately from the repeat tracks and examined along each subtrack to identify jet positions. Figures 5 and 6 show RMS offshore and onshore velocity profiles from subtracks a006 and a149 respectively. Regions where the RMS offshore velocity greatly exceeds the RMS onshore velocity correspond to jets based on an analysis of GEOSAT data during the Coastal Transition Zone experiment. Thus, the a149 data suggest the existence of an offshore jet at 38° and an onshore one at 38.5°. However, because of the sparse and noisy nature of the ERS-1 data set, it is impossible to make this claim with any certainty.

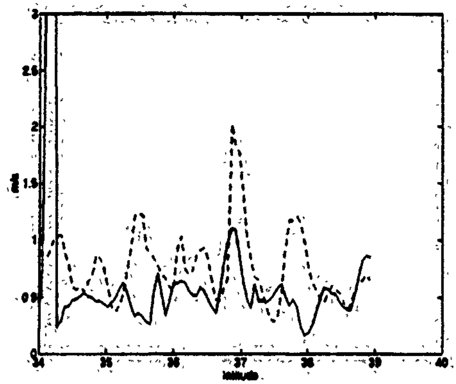

Figure 5: RMS offshore (solid line) and onshore velocity (dotted line) for subtrack a006

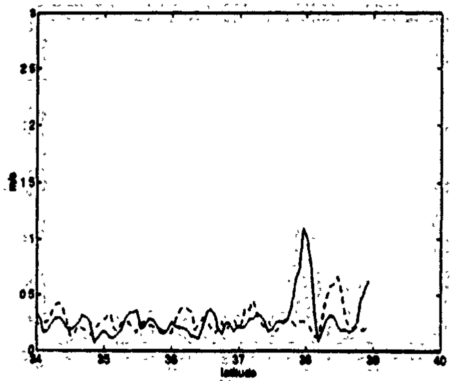

Figure 6: RMS offshore (solid line) and onshore velocity (dotted line) for subtrack a149

6 Program Descriptions

A list of the new routines that have been added to the Altimeter Data processing library of routines to process ERS-1 data is given in Table 5. A detailed description of these routines follows below.

Program	description
ers2geos	Converts IGDR format files to GDR format files
ig_region	Separates raw ERS GDRs into sequential orbits in a specified region
ig_repeats	Performs repeat-track analysis using a sinusoidal orbit correction
ig_spline	Splines GDRs to a uniform latitude grid

Table 5: List of ERS-1 programs

6.1 ers2geos

This program reads in an ERS-1 data file in IGDR format and writes out the data in GDR format. The mapping of IGDR fields to GDR fields is carried out as shown in Table 1. The parameters connected with wind speed statistics (fields 8, 9, and 10), corrections to the height relative to the reference ellipsoid (field 20), integrated electron density (field 22), and peakiness (field 23) are discarded. The flag, which is included as a part of an IGDR, is stored separately to conform with the GDR format. Table 2 shows the mapping of the flag bits. Information from only two flag bits is retained, bit 0, which indicates presence of water, and bit 1, which indicates shallow water. Column three in both tables can be used as a cross-reference to Table 1 in [1]. This program reads in a binary data file from *stdin* and writes out a binary file to *stdout*. The usage is

% ers2geos < *igdr_file* > *gdr_file*

6.2 ig_region

This program is modified from the GEOSAT program, goregion. It reads in raw ERS GDRs and separates them into individual ascending and descending orbits and extracts data from a user-specified region. The first record is examined for the time stamp, which determines the phase of the satellite. Based on the phase,

the orbital parameters are set and the data is divided into cycle and orbit numbers and labeled according to the conventions described in Table 4. The region may be specified in two ways, as bounded by latitude lines or bounded by longitude lines. Usage for this program is:

```
% ig_region dir min_lat max_lat min_lon max_lon [orb_num]
```

where:
`dir` is 1 for regions bounded by latitude lines, 2 otherwise;
`min_lat` is minimum latitude, in degrees, for the region to be extracted;
`max_lat` is maximum latitude, in degrees, for the region to be extracted;
`min_lon` is minimum longitude, in degrees, for the region to be extracted;
`max_lon` is maximum longitude, in degrees, for the region to be extracted; and
`orb_num` are the optional orbit numbers, which are extracted from the region.

6.3 ig_repeats

This program is modified from the GEOSAT program, g_repeats. It needs two additional input arguments, the phase and year of the data. It performs a repeat track analysis of the ERS GDRs and assumes that all GDRs have been cleaned, corrected, and splined to a uniform grid using g_clean, g_correct, g_spike, and ig_spline [1]. The program reads in all the available GDRs for a particular track and calculates the mean sea surface height for each grid point. This mean height is subtracted from each track to produce a residual height profile. A sine function is then fit to the residuals as an estimate of the orbit error, and subtracted from them to yield further residuals. The usage of the program is:

```
% ig_repeats phase year p1/c*/c*.a002c > a002cs_m
```

where
`phase` denotes the phase (1 or 2) of the data and
`year` is the year (92 or 93) of the data.
The filename is specified using wildcards so that all cycles associated with the specified orbit are read in. Thus, in the above example, cycles associated with ascending orbit, a002c are read in. The sea surface height mean is written to *stdout*, a002cs_m in this example. It contains the following information:

x_i $lat(x_i)$ $lon(x_i)$ $g(x_i)$ $\sigma^2(x_i)$ Σx^2 $N(x_i)$

where x_i is a sequential counter of the points in the orbit section. $lat(x_i)$ and $lon(x_i)$ are the latitude and longitude at x_i, $g(x_i)$ is the estimated geoid, $\sigma^2(x_i)$ is the sea surface height variability, Σx^2 is the sum of the squares of the sea surface heights, and $N(x_i)$ is the number of cycles of good data found.

In addition, the sea surface height residuals are written to a file in the same directory as the original raw data. The sea surface height residuals contain

x_i $lat(x_i)$ $lon(x_i)$ $h'(x_i,t)$ $f_1(x_i,t)$ $f_2(x_i,t)$

where x_i, $lat(x_i)$, and $lon(x_i)$ are the same as described above, $h'(x_i,t)$ is the corrected sea surface height, and $f_1(x_i,t)$ and $f_2(x_i,t)$ are the two weighted sinusoidal fits.

6.4 ig_spline

This program is modified from the GEOSAT program g_spline. It differs from g_spline in that it needs the phase of the data as part of the input arguments. The function of the program is still the same. It splines GDRs to an uniform latitude grid, filling in missing or bad data points with the flag value 32767. Input data is read from *stdin* and output splined data written to *stdout*. The usage is:

```
% ig_spline phase dir min max gap delta_t
```

where:
phase is 1 or 2;
dir is 1 for regions bounded by latitude lines, 2 otherwise;
min, max are the minimum and maximum latitude or longitude to spline between;
gap is the maximum time in seconds between continuous data segments and
delta_t is the interpolation time step.

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[1] Caruso, M. J., Sirkes, and Z., Flament, P., Altimeter Processing Tools for Analyzing Mesoscale Ocean Features, Tech. Report WHOI-90-45, Woods Hole Oceanographic Institution, Woods Hole, MA, 1990, pp

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16. Abstract (Limit: 200 words)

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California current

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